Small Galaxy Groups
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N-body simulations of interactions and mergings in small galaxy groups

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Abstract. In this paper I focus on three topics related to the dynamical evolution of small galaxy groups, for which the input of N-body simulations has been decisive. These are the merging rates in compact groups, the properties of remnants of multiple mergers, and the evolution of disc galaxies surrounded by one or more satellites. The short dynamical times of compact groups make it difficult to understand why such groups are observed at all. N-body simulations have pointed out two possible classes of solutions to this problem. The first one proposes that there is ongoing formation of compact groups, or that the longevity of the group is due to secondary infall. For the second class of solutions the longevity of compact groups is due either to their specific initial conditions, or to a massive common halo, encompassing the whole group. I discuss here these alternatives, together with their respective advantages and disadvantages. I then turn to the structure of remnants of multiple mergers and compare the results of N-body simulations with the properties of observed elliptical galaxies. Finally I discuss the dynamical evolution of a disc galaxy surrounded by one or more spherical satellites.

1. Introduction

It is now well established that galaxies are not island universes and that their dynamical evolution is strongly influenced by their environment. The complexity of the processes at hand hampers analytical approaches and makes N-body simulations particularly well suited for such studies. Thus interactions and mergings of galaxy pairs have been a favoured goal for simulations (cf. Barnes & Hernquist 1992, Barnes 1998 and references therein). It was, however, necessary to wait until computer hardware and software reached an adequate level before the evolution of small galaxy groups could be simulated with sufficient resolution. In the following I address three problems for which N-body simulations have deepened our understanding. In section 2, I discuss the merging rates in compact groups, and present two classes of possible solutions to the problem of short merging times. In section 3, I present the results of N-body simulations of multiple mergers and compare the structure of the remnants to that of elliptical galaxies. Finally in section 4, I discuss the dynamical evolution of a small group composed of a target disc galaxy surrounded by one or more satellites, as a function of the mass and orbit of the satellites. I particularly focus on the time

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necessary for the companion(s) to spiral to the center of the target, and that as a function of their mass.

2. Merging rates in compact groups

Compact groups are systems of a few galaxies in a tight configuration. Shakhbazian and collaborators (see Hickson 1997 — hereafter H97 — and references therein), Rose (1977), Hickson (1982, 1993) and Prandoni, Iovino & MacGillivray (1994) produced catalogs of such groups. The work of Hickson in particular motivated a number of observational and theoretical studies, reviewed in H97.

An estimate of their dynamical time t_d can be given as $t_d = R/V$, where R some characteristic size of the group and V a characteristic internal velocity. The former is just a few times the typical size of a galaxy, while the intrinsic three-dimensional velocity dispersion is of the order of 300 km/sec (Hickson et al. 1992), giving dynamical times which are only a fraction of a Gyr. The survival of compact groups over a Hubble time thus becomes a problem, which has been addressed by a number of N-body simulations. It was initially proposed that such groups are chance alignments within loose groups (e.g. Mamon 1986, 1995) or filaments seen edge-on (Hernquist, Katz & Weinberg 1995; Ostriker, Lubin & Hernquist 1995). However the large fraction of member galaxies showing morphological signs of interactions (e.g. Mendes de Oliveira & Hickson 1994; H97 and references therein; Verdes-Montenegro, these proceedings) and particularly the large fraction of compact groups showing an extended diffuse X-ray emission (H97 and references therein) argue very strongly against this hypothesis. We will thus concentrate here on other possibilities and on the input of N-body simulations.

The first simulations (e.g. Carnevali, Cavaliere & Santagelo 1981, Ishizawa et al. 1983, Ishizawa 1986) showed that galaxies within compact groups interact and then merge within a very short time, so that the final stage of the evolution, which is a single large object, is reached very fast. As computers progressed it was possible to use more particles per galaxy, and also to run more simulations, thus allowing a better coverage of the corresponding parameter space. Such simulations pointed to two possible classes of solutions to the merging rate problem in compact groups.

2.1. On-going formation of new compact groups

One possible solution is that compact groups are continuously forming, in which case the observed groups would have formed only recently, the older groups having already merged. This was first proposed by Barnes (1989), who suggested that the precursors of compact groups are loose groups. More recently Diaferio, Geller & Ramella (1994) used the results of their N-body simulations to argue that compact groups can form continuously in rich collapsing groups. An interesting question — whose answer should shed considerable light on this problem — is how the properties of the rich collapsing groups used by Diaferio, Geller & Ramella (1994) affect the properties of the resulting compact groups, and which subset of the initial conditions of rich collapsing groups leads to the observed compact groups.

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In a somewhat similar vein Governato, Tozii & Cavaliere (1996) used N-body simulations to follow the evolution of small galaxy groups, each of which is initially starting as a spherical over-dense region. There is initially a collapse, followed by a secondary infall of the surrounding mass. The latter is substantial in a high density universe and assures the longevity of the group, contrary to the case of a low density universe, where the secondary infall is not sufficient.

2.2. Extending the merging time

An alternative solution would be to extend the merging time. One could start by asking what influences the merging rate and whether some N-body simulations have given too short merging times because of the initial conditions they have used. The first step in that direction was made by Barnes (1985), who used a variety of initial conditions and showed that a massive common halo, encompassing the whole group, generally delays the mergings. This was later confirmed by further simulations by Bode, Cohn & Lugger (1993).

Governato, Bhatia & Chincarini (1991) explored rather specific initial conditions and found that the group they simulated lasted 9 Gyrs. Their group consisted of four galaxies with unequal masses. The two big galaxies had 75% of the total mass of the group, the remaining 25% being shared equally between the two small galaxies. One can thus describe the group as a binary with two small satellites. It is expected that such a group can last for a very long time for an appropriate orbit of the binary, since the satellites are too small to produce any substantial perturbation, and this was indeed verified by the simulation of Governato et al. They further tested that the initial conditions of the satellites did not influence the results, and that a group of four equal mass galaxies merged considerably faster, as expected.

Athanassoula, Makino & Bosma (1997, hereafter AMB97), using a very large number of simulations, set out to determine what influences the merging rate in compact groups and how. Their simulations started out with five identical spherical galaxies. The halo was either common to the whole group (hereafter common halos), or attached to each galaxy individually (hereafter individual halos). They considered different ratios of halo-to-total mass, different extents of individual halos, different density distributions in the common halo, different distributions of the centers of the galaxies and different initial kinematics (i.e. groups in isotropic virial equilibrium, as well as expanding, collapsing or rotating groups). In order to be less influenced by the random distribution of the galaxy centers AMB97 made five realisations of each case. This gave them a large number of simulations from which to draw conclusions, but even so does not cover fully the whole possible parameter space.

AMB97 found that in general groups with individual halos merge faster than groups with common halos, and that rotating groups merge slower than non-rotating ones. They also found that groups with common halos merge slower if these halos are not too centrally concentrated and if they have a high halo-to-total mass ratio. In order to see how much all of this can influence the merging rates, they built a group with a high halo-to-total mass ratio and with a common halo which was not too centrally concentrated, and found that it survives without merging for much longer than a Hubble time.

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It is thus possible that, for appropriate initial conditions, the longevity of a compact group is not a problem, thus providing a possible explanation to why so many compact groups are observed in the local universe.

2.3. Advantages and disadvantages of the above solutions

Let us first consider the scenario in which compact groups are continuously formed at a sufficient rate to make up for the ones that are rapidly merging. Its advantage is that a number of observational studies (H97 and references therein) have shown that compact groups are often associated with loose groups. Nevertheless this applies to a fair fraction of the groups, but not all. H97 noted two potential problems with this scenario. The first one was already raised by Sulentic & Rabaça (1994) who, studying the optical luminosity function of galaxies in compact groups and comparing it with that of isolated ellipticals, found no population of field ellipticals that are sufficiently bright to be the product of the merging of a whole compact group. The second point is that, if the merging times are short and new compact groups form continuously, then there must be a lot of merger remnants around (Mamon 1986). Would that not lead to too many remnants? Where are such remnants hiding?

Two possible fossils of galaxy groups have been so far reported. Ponman et al. (1994) observed RX J1340.6 + 4018 both in X-rays and optically and find it to have a high X-ray luminosity, comparable to those of the brighter compact groups, while its optical properties are typical of those of giant elliptical galaxies. A second candidate, NGC 1132, was reported by Mulchaey & Zabludoff (1999), again with the help of X-ray and optical observations. More candidates may of course show up. Nevertheless present results indicate that the number of fossils of compact galaxy groups can not be sufficient to account for a large number of collapsed groups, if the merging rate is high.

The secondary infall solution depends on the value of Ω, since it can only work for Ω of the order of 1. Furthermore in this model the merging starts rapidly leading to at least one merger remnant, but it is effectively terminated when the infall becomes dominant. Thus it should lead preferentially to compact groups with one (or a couple of) large elliptical(s) surrounded by smaller galaxies; a picture which is far from being always true in observed Hickson groups.

The solution of specific initial conditions will work only if there is a binary system dominating the dynamics, which is also not always the case in observed Hickson groups.

The solution proposed by AMB97 will work, as discussed in the previous section, provided compact groups have common halos which are sufficiently massive and not too centrally concentrated, and perhaps appropriate kinematics of the galaxy distribution. The existence of heavy common halos has been well established for many compact groups, either with the help of X-ray observations (e.g. Mulchaey et al 1993, Ponman & Bertram 1993, Pildis, Bregman & Evrard 1995) or optical observations (e.g. Perea et al. these proceedings, H97). They should, in many if not most cases, be sufficiently massive for the AMB97 solution to hold, particularly since the mass of the observed hot gaseous halo should be added to that of the dark matter, as it shares the necessary dynamical properties. Thus this solution looks very promissing. Nevertheless a definite answer can only be obtained with modelling of individual cases, which must await, on

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the observational side, well established radial profiles for the dark matter, and, on the N-body side, a large number of simulations with common halos of different masses and radial profiles, and different kinematics of the galaxy distribution.

First-ranked galaxies observed in compact groups do not appear to be merger remnants since they are not preferably ellipticals or S0s (H97). This can be difficult to understand in the framework of the theories of continuous formation or of secondary infall, but follows easily from the theories of specific initial conditions and of massive common halos. Furthermore Zepf & Whitmore (1991) noted a lack of recent mergers amongst all compact group galaxies. This is in contradiction with the theory of continuous formation, but in agreement with the other three.

Finally let me note that it is not necessary that one single solution explains all compact groups. Indeed such groups are known to be a heterogeneous class of objects, and different solutions might prevail in different cases.

3. Multiple merger remnants

In this section I will briefly summarise results on the structure of remnants obtained from multiple mergings. The first to address this problem was Barnes (1989), followed by Weil & Hernquist (1994; 1996, hereafter WH96), and Athanassoula & Vozikis (1999 and unpublished, hereafter AV99). I will supplement the results of these studies with a few more recent and yet unpublished results of mine.

WH96 and AV99 have complementary approaches. WH96 have few runs, 6 only for multiple merger cases, but a large number of particles, of the order of 800 000 per simulation. This allows them to resolve structural details in the merger remnants. On the other hand AV99 have more than 300 runs, but, at least in some simulations, with few particles. The number of particles is not the same in all their simulations, but depends on the luminous-to-total mass ratio, and ranges between 16 350 and 250 000. Thus in the simulations with fewer particles they could only calculate bulk properties of the merger remnant and not details in its structure. On the other hand their large number of simulations allowed them to draw some conclusions about how the global properties of the merger remnant depend on whether the halo in the initial compact group was common to the whole group or distributed around each individual galaxy, on the luminous-to-total mass in the system, on the central concentration in the compact group, and on its initial kinematics (virial equilibrium, expansion, collapse, or rotation). In the study I am currently pursuing I combine the positive aspect of the two studies, i.e. the large number of particles of WH96 with the large number of simulations of AV99.

A further difference between the WH96 and the AV99 studies is that in WH96 the simulations were preselected so as to ensure a very fast merging after the beginning of the simulation. This is definitely not the case for AV99. Thus in WH96 the individual mergings occurred one soon after another, while in AV99 the time between individual mergings was variable, in some cases allowing an equilibrium to be reached before the next merging occurred. This may have an effect on the properties of the final remnant.

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Barnes (1989) showed that the radial profile of the projected density for the main body of the remnant could be well approximated by an $r^{1/4}$ law, in good agreement with observations of elliptical galaxies and with results obtained by simulations of merger remnants of galaxy pairs (e.g. Barnes & Hernquist 1992, Barnes 1998 and references therein). This was later confirmed by WH96 and AV99. The agreement with observations, however, does not extend to the center-most parts, which, in the simulations, show a core rather than a cusp (WH96). The problem is more acute for multiple mergers than for pairs (WH96). For the case of pairs the inclusion of bulges in the progenitor disc galaxies reduces the size of the core region. This is true also for multiple mergers, but to a lesser extent (WH96). Mihos & Hernquist (1994) added a gaseous component to the progenitors in merging pairs, but even so could not find radial profiles which are, in their inner parts, similar to the observed ones, this time because of the formation of an over-dense inner nucleus. The effect of gas in the progenitors of multiple mergers on the center-most part of the merger profile has not yet been explored.

Another question addressed by these studies is the alignment between the minor axis and the angular momentum axis. Observations show that the distribution of the angle between these two axes has a maximum around 0°, with a secondary maximum around 90°(Franx, Illingworth & de Zeeuw 1991). On the other hand the simulations of merging pairs (Barnes 1992) show misalignment angles inconsistent with this picture. Later simulations, however, give only small misalignment angles, arguing that the mass ratio of the progenitors, as well as their properties, have a significant impact on the merger remnant (Barnes 1998). Simulations of multiple mergers (Weil & Hernquist 1994 and AV99) show misalignment angles in good agreement with observations, in all cases where rotation was sufficiently large for its angle to be accurately measured.

4. Small groups consisting of one disc galaxy surrounded by one or more satellites

4.1. One satellite

I have run a series of simulations with a target disc galaxy and a companion. The target consists of a disc and a halo with a mass ratio of 0.7:1.3, and is bar unstable. I thus first evolved it in isolation, so that it developed a bar, and then added the companion, initially in a quasi-circular orbit with a radius including 96% of the total mass of the target galaxy. The companion was in all simulations modeled by a spherical Plummer distribution, of the same scale-length and cut-off radius, and its mass was either equal to that of the target disc, or 29%, or 10% of it. In this series of simulations the orbital plane coincided with the equatorial plane of the target disc and the number of particles in the target was equal to 800 000, out of which 280 000 in the disc. The number of particles in the companion depends on its mass, so that the mass per particle is always the same.

In all simulations the companion spirals inwards towards the center of the target, due to dynamical friction. The time necessary for this depends strongly on both the mass of the companion and the sense of its rotation around the

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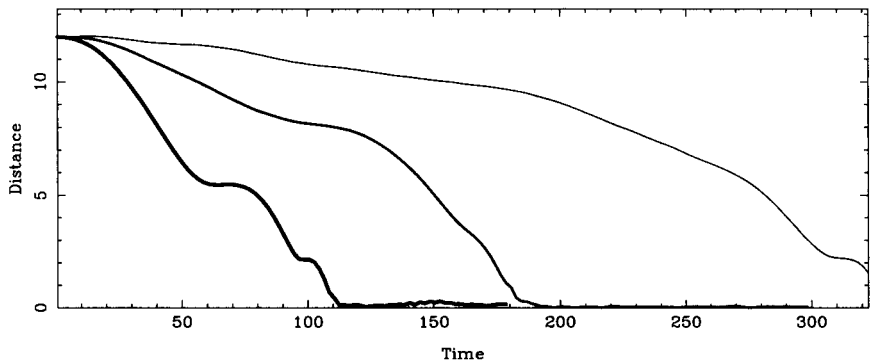

Figure 1. Distance from the center of the companion to the center of the target galaxy as a function of time in systems with only one satellite. The heavy line corresponds to a companion of mass equal to that of the disc and the thin one to a companion ten times less massive. The line of intermediate width corresponds to a simulation with a companion of mass 29% of that of the disc. The unit of length is 3.5 kpc and the unit of time is 1.2 $\times 10^7$ yrs.

target. As can be seen in Figure 1, more massive companions fall in faster, in good agreement with Chandrasekhar's law of dynamical friction (e.g. Binney & Tremaine 1987). Retrograde orbits lead to much longer infall times than direct ones in the case of low mass companions, while the sense of rotation makes no difference in the case of high mass companions.

As the high mass (density) companion spirals to the center of the disc it looses only a small fraction of its mass before it reaches the center of the target. There it occupies the place where a bulge would normally be located. The main change it undergoes concerns its shape, which becomes oblate, due to the extra gravitational attraction of the target disc. At the same time the target disc both thickens and expands, so that its axial ratio is little changed in the process and it still remains a disc. On the other hand the bar is destroyed by loosing a lot of its particles and wraps around the companion. Thus the final radial density profile of the disc has a minimum in the center, and can be thought of as a Freeman type II profile.

The fate of a low mass (density) companion is totally different. As it spirals inwards it looses a fair fraction of its mass and its spherical shape, becoming strongly elongated in the orbital plane. Particles escaping the companion towards the outer parts form a one-armed spiral feature, which with time grows thinner, more tightly wound, expands and gradually disappears leaving behind it a thick disc. Particles escaping the companion towards the inner parts develop, in the case of a direct companion, orbits elongated along the bar and form mass concentrations around the two ends of its major axis. In the case of a retrograde companion the particles escaping it towards the inner parts form a ring-like feature around the bar. The bar itself is not destroyed, but suffers small changes, both in its pattern speed and amplitude.

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The satellite also severely influences the kinematics of the halo, since it gives it some of its orbital angular momentum. Thus the halo acquires a sizeable spin in the case of the high mass satellite and a smaller but still measurable one in the low mass case. As the companion spirals inwards it also increases locally and temporarily the velocity dispersion of the halo. This local maximum spirals inwards to the center of the halo, together with the companion.

4.2. Several satellites

I have run a few simulations where the target disc galaxy is initially surrounded by three satellites. In all simulations one satellite was massive (of mass equal to that of the disc), one had a low mass (equal to one tenth of that of the disc), and the third one had an intermediate mass (somewhat less than a third of the mass of the disc). What changed from one simulation to the other was the initial positions of the companions, including their distances from the center of the target and their relative phases. Since I am only interested in the time evolution of global quantities, like the distances between the companions and the target, I used relatively few particles per simulation. The target was modeled with 120 000 particles, out of which 42 000 in the disc and the remaining in the halo. The number of particles in the companions was 42 000, 12 000 and 4 200 respectively.

As was clear from the short summary given in the previous subsection, simulations with only one satellite give a wealth of interesting features. It is nevertheless relatively easy to draw general conclusions and give a global picture of the results. This is much more difficult to achieve in the case of multi-satellite simulations, where the evolution depends on many more factors. For example in the case with only one satellite one could say that the companion sinks towards the center of the target quasi-monotonically, at a rate depending mainly on its mass and sense of its orbital rotation. As can be seen from the four examples shown in Figure 2, the situation is much more complicated in the case of three companions, since these interact not only with the target, but also with each other, exchanging energy and angular momentum between them. Thus satellites can temporarily move outwards rather than inwards, or lighter satellites can sink faster than more dense ones. Furthermore satellites can merge between them before merging with the target. It is thus not possible to propose a simple, global picture as in the case of a single companion.

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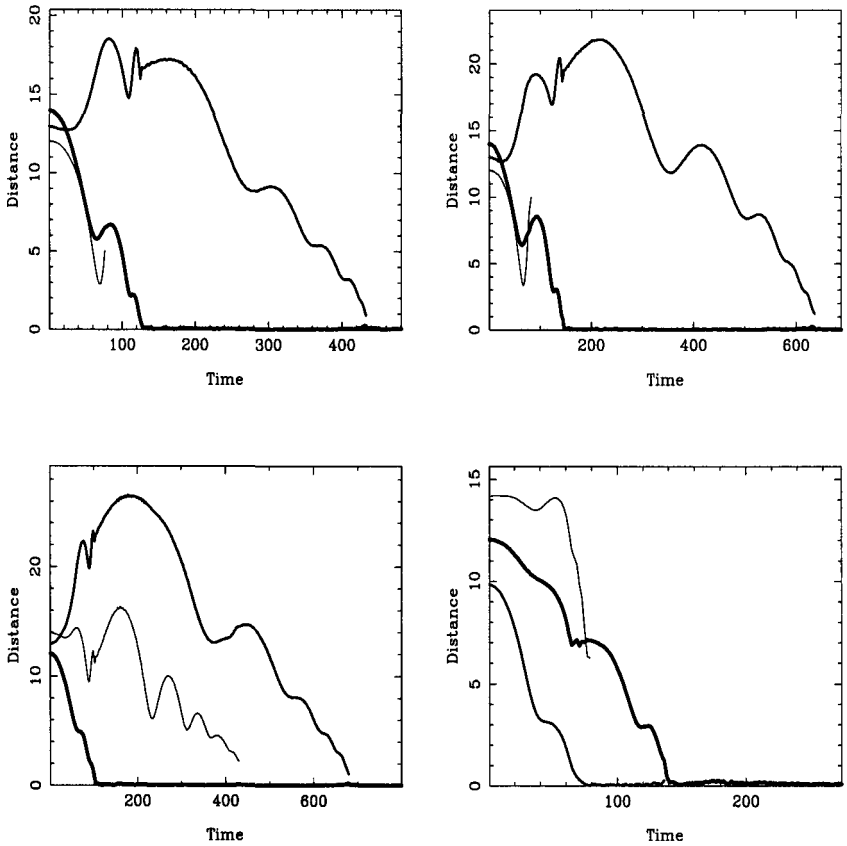

Figure 2. Distance between the center of the companion galaxy and the center of the target as a function of time. Each panel corresponds to a different simulation, each with three companions of different masses and initially at different distances from the target. The thickest line shows the evolution for the companion of mass equal to that of the disc and the thinnest corresponds to the companion which is ten times less massive. The line of intermediate thickness is for the companion of mass equal to 29% of that of the disc. Units are as for Figure 1.

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